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Low Luminosity Radio Loud Active Galactic Nuclei

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I review observational properties of low power radio loud AGN. High resolution VLBI observations allow the estimate of the jet velocity and orientation with respect to the line of sight and the determination of the Doppler factor. These data reveal rich structures, including two-sided jets and secondary components. New results on 1144+35, a giant radio source with superluminal motion are shown in detail.

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1. Introduction

The study of parsec scale properties of radio galaxies is crucial to derive physical properties of the central regions of the Active Galactic Nuclei (AGN) and provides the observational basis of Unified Models. A comparison of parsec (pc) and kiloparsec (kpc) scale morphology and properties is the key to understand the origin and evolution of extended radio sources.

To investigate the properties of radio galaxies at pc resolution it is important to select sources from low frequency radio catalogues where the source properties are dominated by the unbeamed extended emission and are not affected by observational biases related to orientation effects. To this aim, we undertook a project of observations of a complete sample of radio galaxies selected from the B2 and 3CR catalogs with z $<$ 0.1 (i.e. no constrain on the core flux density): the *Bologna Complete Sample* (BCS [6]). This sample consists of 95 sources. At present 60 on 95 sources have been studied with VLBI observations. We observed as a first step sources with an arcsecond core flux density $\sim$ 10 mJy or more at 5 GHz and are observing now with phase reference observations sources with a core flux density in the range 1 to 10 mJy (see e.g. Fig. 1).

2. Sources Morphology

Parsec scale structures are mostly one-sided because of relativistic Doppler boosting effects, however a large number of sources with two-sided jets have been found.

Among observed sources 18 show a two-sided pc scale structure corresponding to $\sim$ 30%. We note that in previous surveys of large samples selected at high frequency as the Caltech survey the percentage of two-sided structures is only of 4.6%. The difference between the percentage of symmetric sources in the present sample and in previous samples is naturally explained in the framework of unified scheme models by the fact that present sources have been selected at low frequency, show relatively faint cores, and are therefore less affected by orientation bias.

In most sources we find a good agreement between the pc and kpc-scale structures. This result supports the suggestion that the large distortions detected in BL-Lac sources are due to small intrinsic bends amplified by the small angle of the BL-Lac jets with respect to the line-of-sight.

3. Jet Kinematics

3.1 Proper Motion

Many AGNs contain compact radio sources with different components which appear to move apart. Multi epoch studies of these sources allow a direct measure of the apparent jet pattern velocity (β_ac). From the measure of β_a we can derive constraints on β_p and θ where β_pc is the intrinsic velocity of the pattern flow and θ is the jet orientation with respect to the line of sight:

$$\beta_p = \beta_a/(\beta_a cos\theta + sin\theta) \tag{3.1}$$

A main problem is to understand the difference between the bulk and pattern velocity. In few cases where proper motion is well defined and the bulk velocity is strongly constrained, there is a general agreement between the pattern velocity and the bulk velocity (see e.g. NGC 315 [1],

and 1144+35, here). However, in the same source we can have different pattern velocities as well as stationary and high velocity moving structures. Moreover, we note that in many well studied sources the jet shows a smooth and uniform surface brightness and no (or very small) proper motion (as in the case of Mrk 501, [7]).

3.2 Bulk Velocity

Assuming that the jets are intrinsically symmetric we can use relativistic effects to constrain the jet bulk velocity βc and orientation with respect to the line of sight (θ), as discussed e.g. in [5].

I will discuss here only the jet – counter jet (cj) brightness ratio and the core dominance since they are the mostly used methods.

- Assuming that the jets are intrinsically symmetric we can use the observed jet to cj brightness ratio R to constrain the jet bulk velocity βc and its orientation with respect to the line of sight:

  $$R = (1+\beta cos\theta)^{2+\alpha}(1-\beta cos\theta)^{-(2+\alpha)} \tag{3.2}$$

  where α is the jet spectral index (S(ν) $\propto$ $\nu^{-\alpha}$).

- The core radio emission measured at 5 GHz, at arcsecond resolution is dominated by the Doppler-boosted pc-scale relativistic jet. The source radio power measured at low frequency (e.g. 408 MHz), instead, is due to the extended emission, which is not affected by Doppler boosting. At low frequency the observed core radio emission is not relevant since it is mostly self-absorbed. Given the existence of a general correlation between the core and total radio power discussed in [4], we can derive the expected intrinsic core radio power from the *unboosted* total radio power using the estimated best fit correlation (continuum line in Fig. 2):

  $$logP_c = (0.62\pm 0.04)logP_t + (7.6\pm 1.1) \tag{3.3}$$

  The comparison between the expected intrinsic core radio power and the observed core radio power will give constraints on the jet velocity and orientation ([4]).

The large dispersion in the core radio power visible in Fig. 2 is expected because of the strong dependance of the observed core radio power on θ and β.

From the data dispersion, assuming that no selection effect is present in the source orientation (θ = 0° to 90°), we can derive that the jet Lorentz factor Γ has to be in the range 3 to 10 otherwise we should observe a smaller or larger core radio power dispersion.

4. Results

To derive statistical properties of radio jets on the pc scale, we used all observational data for the 60 sources in our sample with VLBI data. We found that in all sources pc scale jets move at high velocity. No correlation has been found between the jet velocity and the core or total radio power. Highly relativistic parsec scale jets are present regardless of the radio source power. Sources

with a different kpc scale morphology, and total radio power have pc scale jets moving at similar velocities.

We used the estimated jet β and θ to derive the Doppler factor δ for each source, and the corresponding intrinsic core radio power (assuming α = 0):

$$P_{c-observed} = P_{c-intrinsic} \times \delta^2 \tag{4.1}$$

We found a good correlation between $P_{c-intrinsic}$ and P_t with a small dispersion since plotting $P_{c-intrinsic}$, we removed the spread due to the different orientation angles (Fig. 3).

These results are in agreement with the expectations from unified models.

5. Low power radio cores

The previous results are supported by the studies of many sources. However studying sources with a faint arcsecond scale radio core never studied before in a large sample, we are having a relatively large number of peculiar pc scale structures which interpretation and connection with the lage scale structure it is not clear. The present low number of studied sources does not allow to distinguish between a general property of sources with a mJy (or lower) radio core and the presence of a few peculiar sources, possibly with evidence of restarted activity.

Here we present the radio image at kpc and pc resolution of 3C310. A more detailed discussion will be presented and discussed in Giovannini et al. (in preparation) together with other peculiar structures in our sample (e.g. 1346+26 and 0836+29B).

At kpc scale 3C310 is an extended relaxed double source with a bright core and a short jet in N direction (see Fig. 4). The lobes show a filamentary structure, moreover total flux density measures from the NED database show that 3C310 has a steep radio spectrum ($\alpha > 1$). These two evidences suggest that the radio lobes are old, but a detailed study is not available in literature.

As noted by [9] for the optical image, this galaxy is flattened east-west, on an almost perpendicular direction to the kpc radio jet axis.

VLBI images (see also [8]) show an extended structure elongated perpendicularly to the kpc scale radio structure and to the short jet visible in the VLA image (see Fig. 5). The pc scale structure is very peculiar since a dominant core structure is not visible even at 5 GHz. With present data it is not possible to identify a core emission moreover the extended emission is resolved and looks quite different from most pc scale jets detected in radio galaxies. The low brightness and the absence of evident boosting effects suggest an orientation near to the plane of the sky, but in this case the large difference in the position angle of the pc and kpc scale structure has to be real and not amplified by projection effects. More data at different resolution are necessary to understand the pc scale structure and its connection with the kpc scale radio lobes.

6. 1144+35

The low power radio source B2 1144+35B was identified with a faint (m_{pg} = 15.7) Zwicky galaxy (ZW186.48) in a medium-compact galaxy cluster at a redshift of 0.0630.

From the radio point of view, 1144+35 has a peculiar structure as discussed in detail by [3]. New observations confirm the general structure discussed in [3]. The parsec scale structure (Fig.

6a) is resolved in a nuclear source (C) with a short jet (D) and counter-jet structure (E). At about 25 mas from the core we have an extended jet like structure (A and B components) which is the dominant structure in the VLBI images. This jet structure is extended, clearly limb-brightened and connected to the core by a low brightness emission.

We used the observations made at different epochs to measure the apparent proper motion of components A, B, and E with respect to the core component C. In Fig. 6b we show the distance of components A, B, and E from C at different epochs. From these data we measured for the first time a proper motion of the counter-jet (E) structure (in agreement with the previous upper limit): β_{a-cj} = 0.23 while for components A and B we confirm (note the different cosmology used here with respect to previous papers): β_{a-j} = 1.92.

Since we know the source Angular Distance (D) in the present cosmology we can also derive the intrinsic jet orientation [10]:

$$D = 0.5c \tan\theta(\mu_a - \mu_r)(\mu_a \mu_r)^{-1} \tag{6.1}$$

where μ is the angular velocity of the approaching (a) and receiding (r) jet.

We find θ = 33° and therefore β = 0.94 in agreement wth the measured jet – counterjet arm ratio $\sim$ 10 which implies $\beta cos\theta \sim 0.82$ with the possible values: β = 0.95, θ = 30°.

The morphology of this source suggests a recurrent radio activity. We have:

- The Mpc scale (the oldest structure)
- The naked jets and the dominant core on the arcsecond scale
- The VLBI structure discussed here.

Assuming a constant jet velocity the main VLBI jet structure was emitted from the core about on 1950.

One more evidence of a recurring activity is from the arcsecond core and mas structure flux density variability (Fig. 7). From the comparison of the light curves of the arcsecond scale core and the mas scale components it is clear that: 1) the arsecond scale variability in not due to the mas core C but to the main jet component (A); 2) in the last few years (after 2002) the flux density of the mas core C is increasing and the increase of the flux density is visible also from the arcsecond core monitoring but only at high frequency.

A possible explanation is that after 2002 and before of 2006 the core C started a new active phase and a new component is coming out. This new component is not yet visible in our images and it is still self-absorbed at frequencies lower than 8.4 GHz which implies in equipartition conditions a size of this new component of about 0.03 mas. If this component is moving at the same velocity of the main jet we should start to see it in VLBI images at 8.4 GHz in about 2 years.

7. Conclusions

- The parsec scale jet morphology is the same in high (FR II) and low (FR I) power sources; the pc scale morphology is in agreement with expectations from unified models

- There is a good agreement between the pc and kpc scale orientation
- The pc scale jet velocity is highly relativistic in FR II and FR I sources. It is not related to the total or core radio power of the source. No correlation was found with the kpc scale structure
- In some sources with a low power nuclear source we find a peculiar morphology: restarted activity and a complex mas scale structure not yet understood, misaligned with the kpc scale structure.
- The low power source 1144+35 shows a superluminal motion and a restarted activity. The core flux density is variable and an increase of the core flux density at high frequency suggests the presence of a new component which could be visible in VLBI images in 2007-2008

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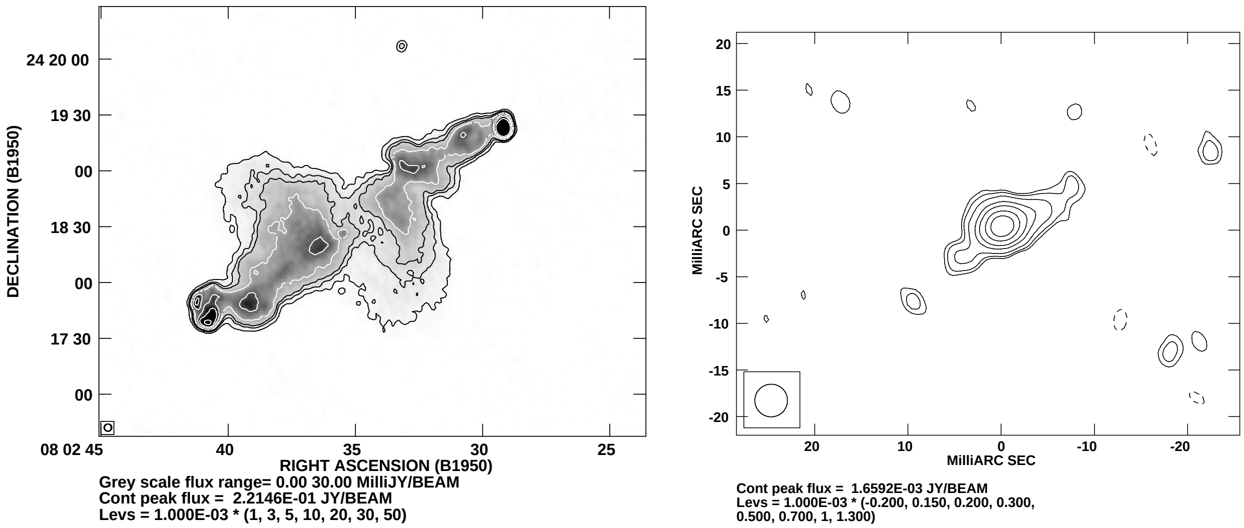


a. VLA b. VLBI.

Figure 1: VLA image of the kpc scale structure of 3C192 from http://www.jb.man.ac.uk/atlas (a). Phase reference VLBA image of the core of 3C192 (b).

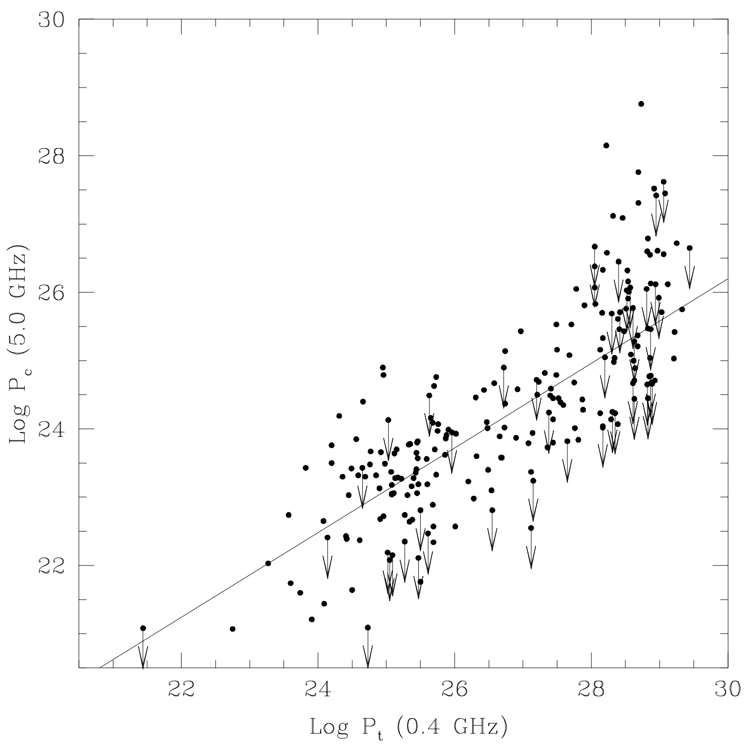
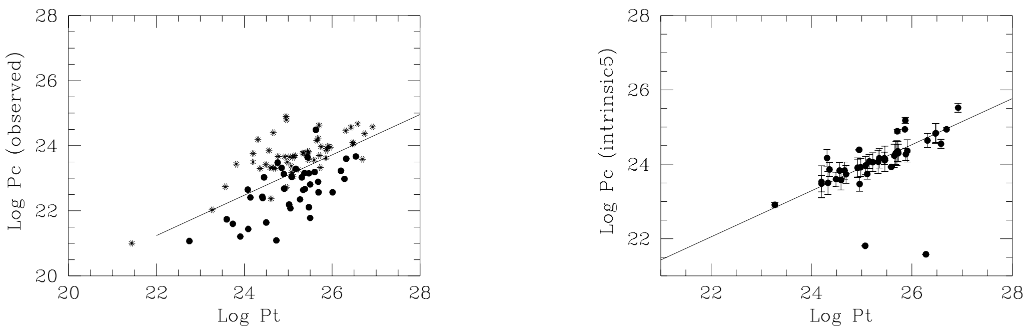


Figure 2: Arcsecond core radio power at 5 GHz (P_c) versus total radio power at 0.4 GHz (P_t) for B2 and 3CR radio sources (see [2]). Arrows are upper limits when a nuclear emission was not detected. The line is the best fit of the data corresponding to a soource orientation with respect to the line of sight of 60°.



a. observed data b. intrinsic data.

Figure 3: Observed core radio power versus total radio power for sources from the BCS with VLBI data (a). As (a) but with intrinsic core radio power versus total radio power (b).

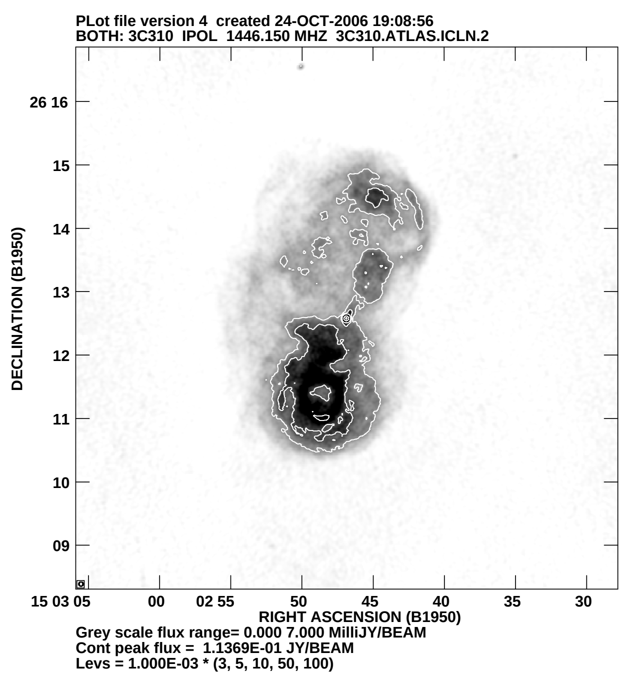
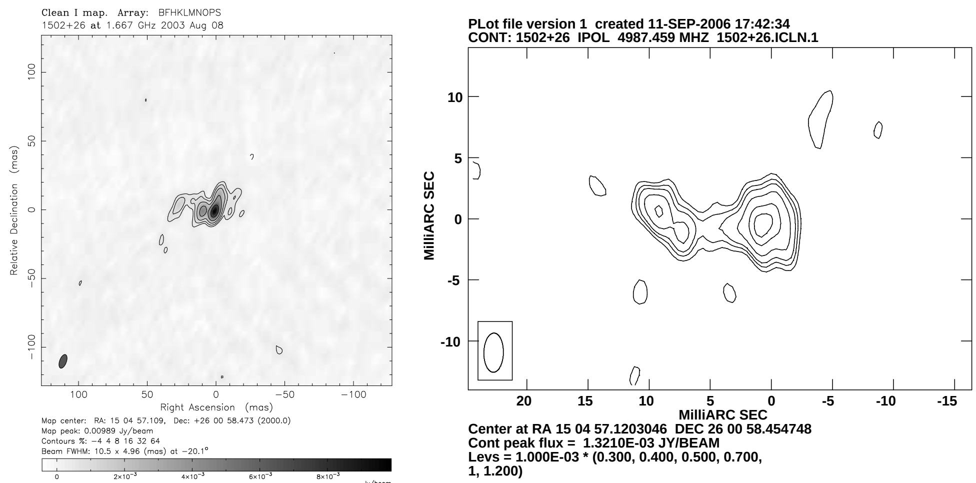
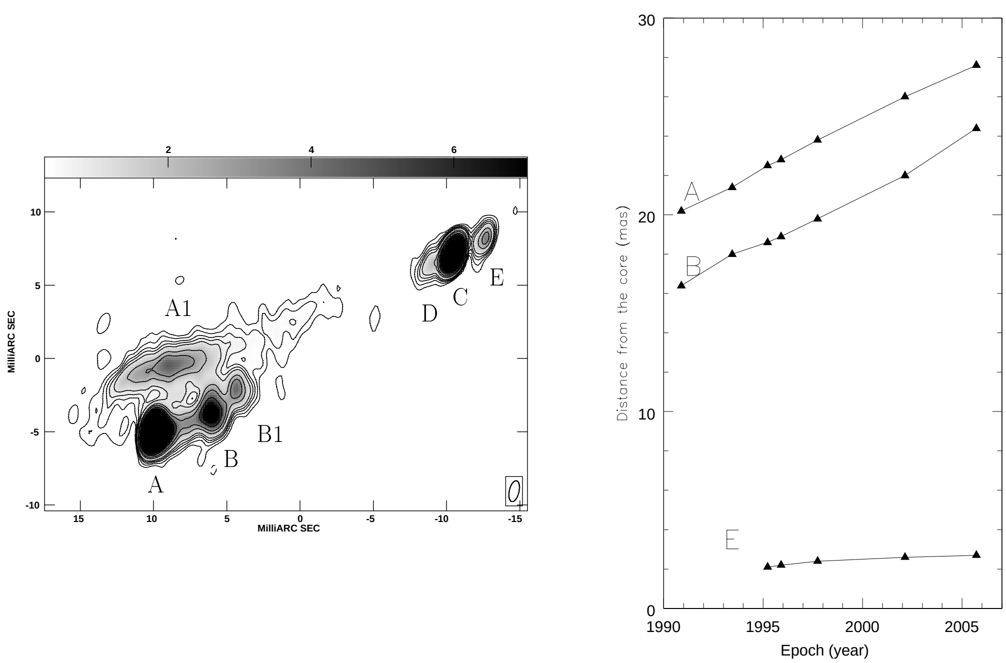


Figure 4: VLA Arcsecond radio image of 3C310 from http://www.jb.man.ac.uk/atlas.



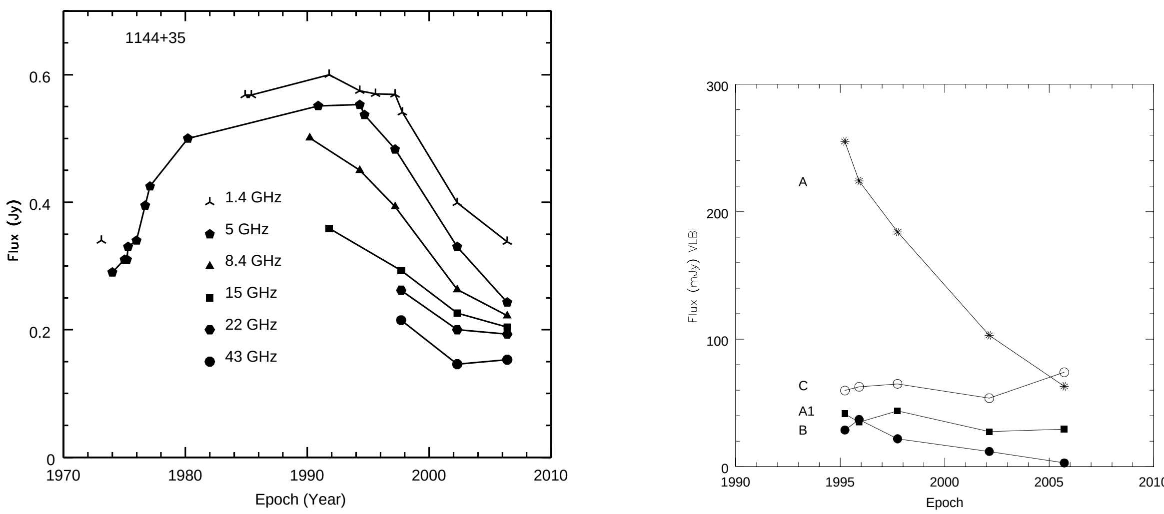
a. VLBI image at 1.4 GHz c. VLBI image at 5 GHz.

Figure 5: Phase reference VLBI images at 1.4 GHz(a) and at 5 GHz (b) of 3C310.



a. VLBI at 8.4 GHz b. Proper Motion.

Figure 6: VLBI image of the pc scale structure of 1144+35 (a). Core distance of components A, B, and E at different epochs (b).



a. Arcsecond core b. VLBI components.

Figure 7: Flux density measures of the 1144+35 arcsecond core at different epochs and frequencies (a). 8.4 GHz flux density measures of components A, A1, B, and C at different epochs (b).